COMPUTER-ASSISTED SOFT TISSUE INTERVENTIONS

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ABSTRACT

Computer-assisted therapy in clinical routine is still limited to structures that remain rigid with respect to reference points. Soft tissue generally shows significant motion due to respiration, heart beat, and the interventional procedure itself. Therefore, computer assistance for soft tissue interventions requires strategies to capture and compensate for motion. Since a general solution to the problem is not available, application specific methods have to be developed. The paper presents approaches for computed tomography (CT) guided liver interventions, bronchoscopy, and laparoscopic radical prostatectomy.

Index Terms— Navigation, image-guided therapy, liver, bronchoscopy, laparoscopic prostatectomy

1. INTRODUCTION

Despite rapid developments in the research areas medical imaging, medical image processing and robotics, computer assistance for soft tissue interventions is still limited to diagnostics and surgical planning. Several studies have demonstrated the efficacy of computer assistance to support the precise and fast targeting of *rigid* structures which remain in a constant position during the intervention. However, most organs show significant movement due to respiration and the manipulation of the tissue by surgical instruments.

To apply navigation techniques to *soft* tissue, intra-interventional organ shift and deformation must be compensated. The methods that have been presented to address this issue include the following:

Gating: Gating techniques are based on the assumption that the organ reoccupies the same position at identical points in the respiratory cycle. This approach is popular because of its simplicity, yet, the underlying assumption may not always be valid.

Real-time target registration: An alternative approach is to utilize a real-time imaging modality such as ultrasound or x-ray to update the image guidance system with the current target position. This method seems very promising, but automatic image-based registration and tracking is not yet sufficiently fast and accurate to be applied for real-time navigation.

External marker tracking: Another approach for supporting soft tissue interventions is to infer internal organ motion from the movement of external markers mounted onto the skin of the patient. While this method may yield accurate results in some cases, it may not be robust enough in other cases because organ motion is not necessarily predictable from the movement of the skin.

Internal marker tracking: An alternative method is to place trackable markers directly into the target organ and estimate the location of the target point continuously from the current positions of these markers. This technique is potentially very accurate, yet, it increases the invasiveness of the intervention.

In this paper, we introduce three navigation approaches for different minimally invasive interventions in soft tissue: Computed tomography (CT) guided liver punctures, CT guided bronchoscopy, and laparoscopic prostatectomy.

2. NAVIGATED LIVER PUNCTURES

CT guided minimally invasive interventions in the liver such as tumor biopsy and thermal ablation therapy are well-established clinical procedures for cancer diagnosis and therapy. One of the main challenges related to these interventions is the exact placement of the needle within the lesion because the liver is subject to respiratory motion. To facilitate the needle insertion process, several research groups (e.g. [1, 2]) are investigating methods for compensating organ motion in computer-assisted interventions.

The approach we propose applies a real-time deformation model to estimate the position of the navigation target point continuously from a set of optically tracked fiducial needles. The workflow is illustrated in Fig. 1: Prior to the intervention, the fiducial needles (*navigation aids*) are inserted in the vicinity of the target (i). Next, a planning CT scan is acquired (ii), which is used to plan a trajectory from the skin to the target (iii). Finally, the tracking coordinate system is registered

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with the CT coordinate system based on the positions of the navigation aids (iv). During the intervention, a real-time deformation model is used to continuously estimate the position of the target point from the current positions of the fiducial needles. Details on the underlying algorithms and our visualization concept can be found in previous reports [3, 4].

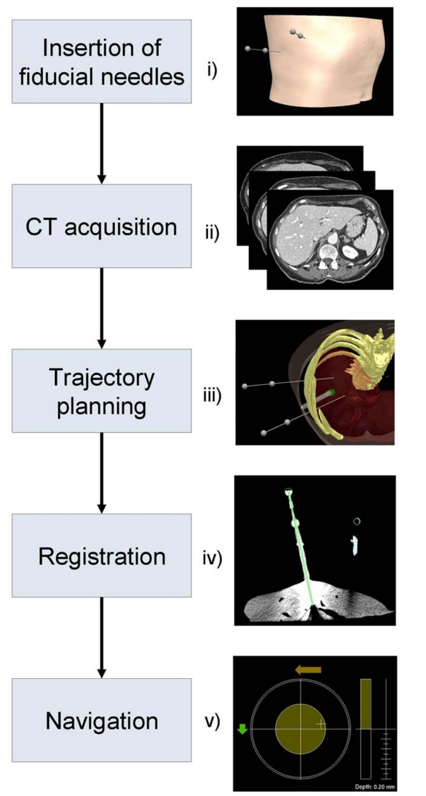

Fig. 1. Navigation concept for liver punctures.

To evaluate our navigation concept, we developed a respiratory liver motion simulator which models the human body and allows for validating image-guided systems ex-vivo. We implanted ten 2-ml agar nodules into three pig livers as tumor models, and two persons used our navigation system to target the center of gravity of each nodule. Organ movement and deformation was generated by the simulator. The lesions were successfully hit in all 20 trials. The final distance between the applicator tip and the center of gravity of the lesion was determined from control CT scans and was 3.5 ± 1.1 mm on average [5].

In a second study, we assessed the targeting precision of our system in-vivo. Eight 2 ml agar nodules were implanted into the livers of two swine as tumor models. One medical expert with experience in punctures and one non-expert used the navigation system to target each nodule twice. The targeting error, which includes the system error and the user error, was defined as the distance between the applicator tip and the center of gravity of the lesions in control CT scans and was 5.3 ± 2.2 mm (n = 16) for the expert, 3.2 ± 1.3 mm (n = 16) for the non-expert, and 4.2 ± 2.1 mm (n = 32) averaged over both subjects [6].

From a clinical point of view, robust targeting precision of the order of magnitude of 4 mm could improve the treatment standard for CT-guided minimally invasive interventions in the liver considerably.

3. NAVIGATED BRONCHOSCOPY

With the help of a bronchoscope the inside of the lung can be inspected in order to perform diagnosis or local therapy. However, the instrument does not provide global information about its position and orientation within the complex structure of the bronchial tree, which makes it difficult to directly approach a previously defined position. Furthermore, the size of the tip of the bronchoscope makes an advancement into the thin periphery impossible. To overcome this problem, smaller catheters are used, which cannot provide an image. In most cases fluoroscopy or computer tomography scanning is used to monitor the current position of the catheter. A navigation system could potentially assist exact guidance and placement, provided it be accurate in real-time and have the ability to compensate for respiratory movement.

Currently developed navigation systems for bronchoscopy can be subdivided by the technique used to determine the position of the instrument. For instance, Merritt et al. register the real image of a video bronchoscope to a predicted virtual image [7]. Mori et al. propose a hybrid tracking system consisting of an electromagnetic tracking system (EMT) with five degrees of freedom (DOF) and an image to image registration in order to calculate the missing sixth degree of freedom (roll angle) [8]. Klein et al. use recorded trajectories of an EMT system for the initial registration of the preinterventional image data [9].

Our approach of navigated bronchoscopy considers the problem of using a static CT scan to navigate inside constantly moving soft tissue [10]. It offers a direct guidance to a preinterventionally defined target inside the bronchial tree to save intervention time spent on searching the right path and to minimize the duration of anesthesia. This approach uses an EMT system, which is used to monitor three 5DOF reference sensors fixed onto the patient's thorax and one custom designed 6 DOF sensor placed inside the working channel of the bronchoscope or inside a catheter.

The respiratory motion compensation algorithm is based on the assumption that the bronchoscope always stays inside the bronchial tree and does not penetrate through the bronchial wall. The tracked position of the instrument is continuously matched onto the center line of the bronchial tree, which is extracted from preinterventionally acquired CT data. A smooth and consistent movement of the virtual representation of the instrument inside the static virtual bronchial tree is realized by means of a Monte Carlo approach.

A preinterventional planning module enables the interactive definition of the navigation target.During the intervention, different visualizations can be used to navigate the instrument to the desired lesion. Reconstructed 2D slices of the CT-scan (see Fig.2 upper left), virtual 3D scenes showing the desired elements as partly transparent surfaces (upper right), a video image of the bronchoscope extended by means of Augmented Reality (AR) (lower left) or a virtual bronchoscopy from the view of the current position of the instrument (lower right) can be used to perform the navigation.

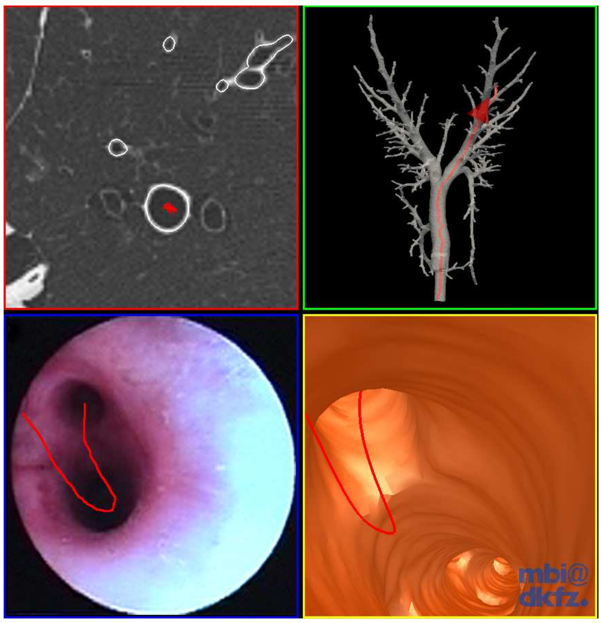

Fig. 2. Screenshot of different views of the navigated bronchoscopy visualization. The current position of the tracked instrument is represented by a cone (upper right) and a red path leads to the defined target lesion.

In order to assess the accuracy of the system we performed ten interventions on an ex-vivo lung phantom. The error for estimating the position of the instrument within the bronchial tree under respiratory movement was computed from control CT scans and was 4.9 mm on average. The mean duration of the interventions was 7.9 minutes. In the near future, the navigation system is to be advanced to also guide a needle into the parenchyma of the lung in order to extract a tissue sample.

4. NAVIGATED LAPAROSCOPIC PROSTATECTOMY

Endoscopic surgery of thoracic and abdominal organs gains increasing importance for surgical interventions. Although patients generally benefit from less invasive surgery due to a faster convalescence, endoscopic surgery comes along with several shortcomings for the surgeon: Limitations in the surgeon's perception, like e.g. a restricted field of view and depth perception and little tactile feedback aggravate the orientation and navigation inside the body cavity. Furthermore, the mobility of endoscopic instruments and camera are limited.

One promising application of computer-assisted soft tissue navigation is the minimally invasive surgical treatment of prostate cancer, which is referred to as laparoscopic radical prostatectomy (LRP). In LRP, a main challenge is to define the line of surgical preparation around the prostate: A preparation near the organ may spare the patient's pelvic innervation and in consequence preserve urinal continence and sexual potency. However, since most tumors reside near the prostate boundaries, it also increases the risk of leaving tumor cells inside the pelvis. Recent research has shown that the intraoperative use of transrectal ultrasound (TRUS) during prostate surgery significantly enhances the understanding of the patient's anatomy and enables a more precise surgical preparation. However, orienting 2D slices of 3D TRUS data is time-consuming, difficult, and prone to errors. Therefore, we developed a navigation system, which provides the surgeon with valuable information regarding the actual position of anatomical structures, which can not be seen in endoscopic video images.

The navigation system consists of an US system, our custom designed needle-shaped navigations aids, and a standard PC; no auxiliary devices are needed. A more elaborative description of the system can be found in [11]. The navigation procedure is divided into the following main steps:

Preoperative Planning: A 3D TRUS dataset is obtained in the course of prostate cancer diagnosis and an initial model of the prostate and nearby anatomical structures, like urethra, rectum, and innervation is prepared.

Navigation Aid Placement and Initial Registration: After granting access to the prostate, the surgeon inserts four navigation aids into the prostate and acquires a 3D TRUS dataset. The preoperative planning and the intraoperative TRUS data including the navigation aids are non-rigidly registered using a landmark-based method. For this purpose, landmarks are defined on the prostate boundaries, which are segmented automatically in the preoperative and intraoperative 3D TRUS datasets as described in [12].

Endoscope Tracking and Enhanced Visualization: The navigation content is visualized as an AR overlay of the endoscopic video image, additionally virtual 3D visualizations from various perspectives are provided. AR requires the real-time determination of the actual (endoscopic) camera position and orientation (pose) with respect to the visualization content. For this purpose, an "Inside-out Tracking" algorithm is applied [13], which iteratively determines the endoscope's pose by use of the spatial configuration of the navigation aids in TRUS data and endoscopic video images. Figure 3 illustrates an AR visualization during LRP.

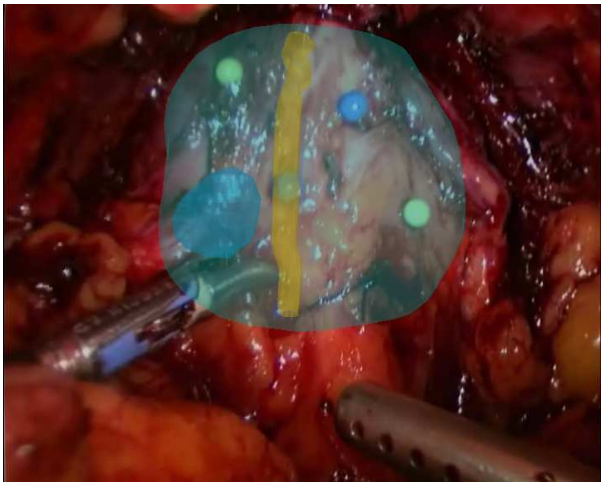

Fig. 3. Experimental trial of navigated laparoscopic radical prostatectomy using the navigation system. Augmented Reality visualization of prostate boundaries (green), urether (orange), biopsy proven tumor nodule (blue). The navigation targets have been manually segmented in transrectal 3D US. Note that this is a static frame of a dynamic video sequence, which provides better perception of anatomical structures.

The system can be easily integrated into surgical workflow, as it does not require external tracking hardware or hand-eye calibrations. Depending on the registration accuracy of the preoperative planning, our evaluations proved the system to visualize the navigation targets with an error of less than 1 mm [11]. Navigation errors due to soft tissue movement are compensated inherently, as the navigation aids move with the organ. Moreover, the validity of the visualization can be verified in real-time: In case of tissue deformations, changes in the spatial configuration of the navigation aids are detected, which preserves the system from an erroneous navigation visualization.

5. CONCLUSIONS

Computer-assisted soft tissue interventions require capturing and compensation for motion. However, real-time 3D imaging and analysis of the relevant structures is not yet feasible in most cases. In this paper, we have presented three approaches which are based on the acquisition of position and orientation information at sparse locations by means of optical or electromagnetic tracking methods. Suitable algorithms were required to estimate tissue motion from these sparse data and to include static image data from preinterventional planning. Generally speaking, tailored solutions for specific interventions have to be developed, where present technical possibilities provide a valuable benefit.

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